



Universitat de Lleida

Document downloaded from:

<http://hdl.handle.net/10459.1/62552>

The final publication is available at:

<https://doi.org/10.2134/agronj2016.09.0537>

Copyright

(c) American Society of Agronomy, 2017

3 Daniel Plaza-Bonilla^{1*}, Jorge Álvaro-Fuentes¹, Javier Bareche², Albert Masgoret², and
4 Carlos Cantero-Martínez²

¹ Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), POB 13034, 50080 Zaragoza, Spain

² Departamento de Producción Vegetal y Ciencia Forestal, Unidad Asociada EEAD-CSIC, Agrotecnio, Universidad de Lleida, Av. Rovira Roure, 191, 25198 Lleida, Spain

9 *Corresponding author: Daniel Plaza-Bonilla. Email address: dplaza.bonilla@gmail.com

11 Keywords

12 Dryland cropping systems; Mediterranean; no-till; sowing date; winter cereals.

14 **ABSTRACT**

The effect of delaying sowing date and maturity class on no-till barley and soft wheat performance was studied over two periods of three years each. A 3 (sowing date) x 2 (maturity class) randomized complete block (RCB) design was run for 3 years with barley (B-) (2006-7 to 2008-9) and soft wheat (W-) (2009-10 to 2011-12) in NE Spain. Sowing dates corresponded to October (D1 - the standard farming practice), November (D2), and December (D3). Maturity classes corresponded to early (-EC) and medium (-MC). Crop above-ground biomass, grain yield and yield components were analyzed. The water-use efficiency of the above-ground biomass and yield (WUE_b and WUE_y), and nitrogen-use efficiency (NUE), were calculated. Averaging barley maturity classes and cropping seasons, D2 and D3 increased their grain yields 59% and 46%, respectively, when compared to D1. A greater number of grains per spike, as well as higher WUE_b and NUE were observed in D2 and D3 compared to D1 in two of the three

barley cropping seasons. Similarly, a greater thousand kernel weight and higher WUE_y was observed when sowing was delayed. Averaged across years, WEC presented a greater yield and above-ground biomass for D2 and D3 compared to D1, while for WMC there were no grain yield differences seen between the sowing dates, above-ground biomass or yield components. Our results demonstrate that, in Western Mediterranean areas, sowing delay under no-till (NT) conditions can increase grain yield, WUE and NUE of winter barley, and also of wheat but only during wet years.

34

35 **Abbreviations**

NT, no-till; NUE, nitrogen use efficiency; TKW, thousand kernel weight, WUE_b , water-use efficiency for above-ground biomass; WUE_y , water-use efficiency for yield.

38

39 **Core ideas**

- 40 • Sowing delay and cultivar effects on cereal production and water and N use
- 41 efficiencies were studied.
- 42 • Sowing delay increased grain yield due to greater number of grains per m².
- 43 • Sowing delay maximized the efficiency in the use of resources

44 Semi-arid Mediterranean agroecosystems are severely limited by soil water
45 availability. Rainfall is characterized by strong interannual and seasonal irregularity,
46 being mainly concentrated in the fall and spring. Winter cereals, represented by barley
47 (*Hordeum vulgare* L.) and wheat (*Triticum* sp.), are well adapted to Mediterranean
48 conditions given the partial synchronization of their cycle with the period of greatest
49 water availability (Cooper et al., 1987).

50 The Ebro valley (NE Spain) is a semi-arid area representative of these
51 Mediterranean conditions where rainfed systems have a precipitation gradient from 300
52 to 700 mm yr⁻¹. In this area, cropping systems are mainly based on winter cereals since
53 the economic benefit of other winter broadleaf crops such as vetch (*Vicia sativa* L.) or
54 rapeseed (*Brassica napus* L.) in severe dryland conditions (with less than 450 mm of
55 annual rainfall) is doubtful (Álvaro-Fuentes et al., 2009). The choice between barley
56 and wheat depends on the severity of the local climate, barley being better adapted to
57 drier conditions than wheat. This means barley monocrops exist in certain areas, with
58 varying proportions of barley and wheat being found as the climate becomes wetter.
59 Conventionally, farmers in the area sow winter cereals early, just after the first fall
60 rains, around mid-October (both for barley and wheat). One of the reasons for this is to
61 reduce the risk of terminal drought during the grain filling period, common in the
62 Mediterranean areas due to high temperatures and a low soil water content at the end of
63 spring (Loss and Siddique, 1994; González et al., 2007), which in some cases is
64 exacerbated by dry winds (McAneney and Arrúe, 1993). In Australian Mediterranean
65 agriculture, greater grain yield and water-use efficiency have been reported when earlier
66 grain filling occurs (Kirkegaard et al., 2014). Moreover, early sowing leads to vigorous
67 crop establishment under warm conditions (Piggin et al., 2015). However, early sowing
68 of cereals can increase susceptibility to biotic attacks (Thackray et al., 2009) related to

69 the warm, wet conditions at the beginning of fall in the western Mediterranean region.
 70 The main problems for winter cereals in the area include various grasses (e.g. ripgut
 71 brome, *Bromus diandrus* Roth.; annual ryegrass, *Lolium rigidum* Gaudin), diseases such
 72 as *Helminthosporium* leaf blights (HLB), and insects such as cereal ground beetle
 73 (*Zabrus tenebrioides* Goeze), although only the first have a significant economic
 74 impact. Earlier sowing impedes complete mechanical or chemical control of weed
 75 seedling emergence and also favors the possibility of earlier pest and disease attacks.
 76 Moreover, until a few years ago, for some particular weeds, such as ripgut brome, there
 77 were no selective herbicides available for barley. As a consequence, their control in NT
 78 systems was based on non-selective pre-sowing herbicides such as glyphosate (N-
 79 (phosphonomethyl)-glycine), with no control during crop growth. Therefore, in some
 80 Mediterranean areas, and in the Ebro valley in particular, winter cereals sown early,
 81 especially as monocrops, led to important infestations of this particular brome (García et
 82 al., 2014).

83 In the Ebro valley, NT has been progressively introduced over the past 30 years
 84 with the aim of both reducing costs and either maintaining or increasing yields
 85 (Cantero-Martínez et al., 2003). The use of long-term NT in semi-arid rainfed
 86 conditions leads to greater soil water storage during the previous harvest-to-tillering
 87 period and increased precipitation storage efficiency compared with traditional
 88 inversion tillage systems based on moldboard ploughing (Lampurlanés et al., 2016).
 89 Greater early crop growth has been observed under NT (Santiveri et al., 2004).
 90 Similarly, water- and nitrogen-use efficiency are also increased (Angás et al., 2006;
 91 Cantero-Martínez et al., 2007). However, early sowing could also increase susceptibility
 92 to insects, diseases and weeds under NT. As a consequence, management strategies
 93 must be improved in order to overcome the limitations posed by those biotic factors

94 while reducing the impact of climatic stresses during the grain-filling period as much as
95 possible. To this end, selecting an adequate sowing date and maturity class appear to be
96 key management practices. Moreover, NT bears traffic load better and leads to lower
97 work intensity (Bueno et al., 2006; Soane et al., 2012; Wolf et al., 1989), widening the
98 window of feasible sowing dates to wetter soil conditions.

99 However, interannual rainfall variability, characteristic of the Mediterranean
100 climate, complicates the selection of an optimum sowing date (Mahdi et al., 1998). For
101 instance, in a Mediterranean area in southern Spain, Ramos et al. (1993) observed
102 greater production of dual-purpose (forage and grain production) triticale when sowing
103 in the last week of November or first week of December compared to earlier sowings. In
104 a study carried out in Syria, Mahdi et al. (1998) studied the effect of different sowing
105 dates on durum wheat grain yield. While in one growing season they observed a 15%
106 reduction in yield when postponing the November 1st sowing by 15 and 30 days, they
107 observed a 16% yield increase in the next growing season. However, these last two
108 studies were undertaken under conventional tillage and were only performed over two
109 growing seasons. In the Mediterranean region, choosing a maturity class is another
110 important decision that must be made by farmers. They used to believe that late
111 maturity classes were the best option for higher yields. The interaction between sowing
112 date and maturity class may affect water-use patterns during crop growth: late maturity
113 classes sown earlier tend to use more water due to greater production of biomass during
114 vegetative stages, reducing the availability of this resource during the grain-filling
115 period; in contrast, early maturity classes seeded later may have less pre-anthesis
116 evapotranspiration. This second case could result in a better balance of water-use
117 between the vegetative and reproductive periods in cereals (Connor and Loomis, 1991).

118 The objective of this work was to evaluate the effect of sowing date and maturity
119 class on grain yield and water- and nitrogen-use efficiency of barley and soft wheat
120 managed under NT conditions. We hypothesized that late sowings and early maturity
121 classes would perform better due to an improved use of soil water and nitrogen.

122 **MATERIALS AND METHODS**

123 **Site conditions and experimental design**

124 A field experiment was established in Agramunt (41° 48' N, 1° 7' E; 330 m asl),
 125 NE Spain. The area is representative of dryland semi-arid Mediterranean conditions
 126 with a mean annual rainfall of 430 mm, potential evapotranspiration (PET) of 855 mm,
 127 and an air temperature of 13.8 °C. The soil was a Typic Xerofluvents (Soil Survey Staff,
 128 2014). The soil water-holding capacity was 185 mm in the first 90 cm of depth. Other
 129 properties of the Ap horizon (0-28 cm) included: bulk density: 1.4 g cm⁻³; soil organic
 130 carbon: 10.5 g kg⁻¹; pH (H₂O:soil, 1:2.5): 8.5; electrical conductivity (1:5): 0.15 dS m⁻¹;
 131 CaCO₃ eq. (%): 40; and loam texture being sand (2000-50 µm), silt (50-2 µm), and clay
 132 (< 2 µm) content: 475, 417 and 118 g kg⁻¹, respectively.

133 Prior to establishing the experiment, the area was devoted to barley production
 134 with summer fallow managed under reduced tillage based on two chisel passes. A 3
 135 (sowing date) x 2 (maturity class) randomized complete block (RCB) design was run for
 136 3 years with barley (B-) (2006-7 to 2008-9) and soft wheat (W-) (2009-10 to 2011-12)
 137 in NE Spain. Sowing dates corresponded to October (D1 - the standard farming
 138 practice), November (D2), and December (D3). Maturity classes corresponded to early
 139 (-EC) and medium (-MC). Sowings of the D1 treatment were carried out between
 140 October 15th and 20th, this treatment being considered a reference as it is typical of the
 141 farming regime in the area. D2 was sown between November 5th and 10th, and the D3
 142 treatment was sown between November 25th and December 5th. In the first period (the
 143 2006-2007, 2007-2008 and 2008-2009 seasons), barley was grown, comparing two
 144 maturity classes: Hispanic (barley early maturity class, BEC) and Sunrise (barley
 145 medium maturity class, BMC). In the second period (the 2009-2010, 2010-2011 and
 146 2011-2012 growing seasons), two soft wheat maturity classes were compared: Bokaro

147 (wheat medium maturity class, WMC) and Artur Nick (wheat early maturity class,
 148 WEC). These medium and early maturity classes correspond to facultative and spring
 149 cultivars, respectively. The experiment was completely randomized in three blocks;
 150 individual plot was 6 m wide x 48 m long. Air temperature and rainfall were recorded
 151 hourly using an automated weather station located in the experimental area.

152 **Crop management practices**

153 The experiment was managed under NT, with the use of a 3 m-wide no-till drill
 154 with disk openers. Three to five days before sowing, the weeds were controlled by
 155 applying 1.5 L ha⁻¹ of glyphosate (N-(phosphonomethyl)glycine). The sowing rate was
 156 450 seeds m⁻² in rows spaced 17 cm apart for the two crops studied. In the first two
 157 seasons (2006-07 and 2007-08) a post-emergence herbicide treatment with tribenuron-
 158 methyl (10 g a.i. ha⁻¹) was applied on 15 February in 2007 and on 23 January in 2008 to
 159 control broadleaf weeds. In 2008-09, a post-emergence herbicide treatment with a mix
 160 of isoproturon plus diflufenican (1243 + 69 g a.i. ha⁻¹) was applied on 19 February. In
 161 2009-10, post-emergence weed control (specifically for ripgut brome, *Bromus diandrus*
 162 Roth.) was carried out with mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15
 163 + 3 g a.i. ha⁻¹) on 5 March. In 2010-11, a post-emergence control of broadleaf and grass
 164 weeds was accomplished with tribenuron-methyl plus metsulfuron-methyl (10 + 5 g a.i.
 165 ha⁻¹) on 30 March. Mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15 + 3 g a.i.
 166 ha⁻¹) was applied on 9 February and on 13 April in D1 and D2 and D3, respectively. In
 167 2011-2012 herbicide applications aimed at reducing ripgut brome levels and control
 168 broadleaf weeds. Tribenuron-methyl plus metsulfuron-methyl (10 + 5 g a.i. ha⁻¹) was
 169 applied 20 February while mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15 +
 170 3 g a.i. ha⁻¹) was applied on 31 January in D1 and on 13 March in D2 and D3.

171 Nitrogen fertilizer was top dressed at the end of February (i.e., the tillering
 172 stage), at a rate of 50 kg N ha⁻¹, in the form of urea-ammonium nitrate solution (32% N;
 173 consisting of 16% urea-N, 8% ammonium-N and 8% nitrate-N) sprayed using stream
 174 bars. This rate was decided upon according to the potential grain yield of the site (i.e., ≈
 175 2.8 Mg ha⁻¹), and the annual N mineralization was estimated to be 30 kg N ha⁻¹ for NT
 176 (Angás et al., 2006). Time of application was chosen to minimize N volatilization
 177 losses. Traditionally, farmers of the region applied greater N rates than the one used in
 178 our experiment and carried out pre-sowing applications. However, more than two
 179 decades of research carried out in a contiguous experimental area has demonstrated the
 180 feasibility to reduce traditional N rates to a half and the inadequacy of pre-sowing
 181 applications given the usually high levels of soil mineral N before sowing (Cantero-
 182 Martínez et al., 1995, 2016; Plaza-Bonilla et al., 2017). Crop growth is limited by the
 183 low temperatures during the period between sowing and tillering in this Mediterranean
 184 region, fact that reduces early N uptake to a minimum.

185 The grain was harvested using a commercial combine at the end of June or the
 186 beginning of July. Crop residues were chopped and uniformly spread over the soil
 187 surface.

188 **Soil and crop sampling and measurements**

189 Soil samples were taken prior to sowing and after harvest in each cropping
 190 season studied. In each plot, two representative areas of 2x2 m were identified and three
 191 soil samples per area were taken using a mechanized soil corer, in 30-cm increments, up
 192 to a soil depth of 90 cm. Once bulked for each depth, part of the sample was dried at
 193 105°C for 48 h to quantify gravimetric moisture. Soil nitrate was determined by mixing
 194 50 g of soil with 100 ml of 1M KCl. The extracts were analyzed using a continuous

195 flow autoanalyzer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). The
 196 soil water and mineral N content of the entire soil profile (0-90 cm) were calculated
 197 using soil bulk density, measured employing the cylinder method (Grossman and
 198 Reinsch, 2002).

199 The dates of anthesis and physiological maturity were recorded for each
 200 treatment and year. Crop above-ground biomass was measured at physiological maturity
 201 by cutting the plants at soil level along a 0.5 m transect of the seeding line in three
 202 locations per plot. Once in the laboratory, the heads were separated from the rest of the
 203 plant (i.e., leaves and stems); both fractions were then dried at 65°C for 48 h and
 204 weighed. After this, in order to calculate the yield components, the ears were counted
 205 and threshed and the number of grains and their weight were recorded. These
 206 measurements allowed the number of spikes m^{-2} to be calculated, as well as the number
 207 of grains per spike, the thousand kernel weight (TKW), and the harvest index (HI). The
 208 grain yield of each treatment was measured by harvesting the plots with a commercial
 209 combine, subsequently weighing the grain and taking a sub-sample to standardize the
 210 values at 10% grain moisture.

211 **Calculation of water- and nitrogen-use efficiency**

212 Water use (WU) during the period between sowing and harvest was calculated as
 213 the difference between soil water content (0-90 cm soil depth) at the beginning of
 214 October and at the harvest of each treatment plus the amount of rainfall received during
 215 that period. As in previous works in the same area, water loss as runoff and deep
 216 drainage was considered negligible due to the negligible slope (< 2%) and the severely
 217 water-limited conditions (Cantero-Martínez et al., 2007; McAneney and Arrúe, 1993).
 218 The above-ground biomass and grain yield at 10% moisture were divided by WU to

quantify the agronomic water-use efficiency for above-ground biomass (WUE_b) and water-use efficiency for grain yield (WUE_y), respectively. WUE calculations were based on soil water content in mid-October (right before sowing D1 treatment). This fact could affect WUE values of D2 and D3 treatments if water losses as evaporation between soil sampling and sowing dates were high. However, under Mediterranean conditions, soil water evaporation is minimum during the period between mid-October until February, when soil water recharge takes place (Lampurlanés et al., 2016). Mean PET from 15 October to 5 December (i.e. from D1 sowing date to the latest sowing date of D3 treatment) amounts 62 mm, according to the records of the nearest meteorological station, which only represents a 7% of mean annual values. Thus, in D2 and D3 the amount of water lost as evaporation would be lower than 62 mm after discounting the fraction accounting for crop transpiration, and taking into account that soil management was based on no-till, which minimizes soil water evaporation (Unger et al., 1991).

Nitrogen use efficiency was calculated as the ratio of grain yield to N supply. N supply was the sum of soil mineral N at sowing (0-90 cm depth), N applied as fertilizer (i.e., 50 kg N ha⁻¹), and mineralized N. This latter was estimated to be 30 kg N ha⁻¹ according to the results obtained by Angás et al. (2006) under similar NT conditions.

Data analysis

The data are reported in dry wt. per unit area except for yield, which was recorded at 10% moisture. The data were checked for normality and analyzed using the JMP Pro 11 statistical package (SAS Institute Inc., 2014). Non-normal data was log-transformed for the analysis and back-transformed for its presentation. To compare the effects of cropping season, sowing date, maturity class, and the interaction of these parameters, an analysis of variance (ANOVA) for a randomized block design was

243 performed for each crop using a general linear model. Differences between treatments
244 were taken to be significant at the 0.05 probability level using a LSD test. Linear
245 relationships between yield components and grain yield were tested using the same
246 software. The slopes of the regressions were tested for differences between sowing
247 dates.
248

249 **RESULTS**

250 **Weather conditions during the experimental period**

251 Air temperatures during the experiment were typical of the Mediterranean
 252 region, with cold winters, hot summers, and intermediate values in fall and spring. The
 253 fall and winter months showed the lowest temperature range (Fig. 1). Rainfall in the
 254 2006-2007, 2007-2008 and 2008-2009 seasons when barley was cropped was 409, 333
 255 and 528 mm (Fig. 1a, 1b and 1c). The first two cropping seasons were characterized by
 256 dry fall and winter periods, although the 2008-2009 season received 78 mm more winter
 257 rainfall than the historical average (Fig. 1c). However, the three cropping seasons
 258 presented greater spring rainfall (233, 219 and 218 mm for 2006-2007, 2007-2008 and
 259 2008-2009) than the historical value (138 mm), coinciding with the anthesis stage of the
 260 crop.

261 Cumulative rainfall during the three wheat cropping seasons was highly
 262 heterogeneous. The 2009-2010 season was considerably wetter (703 mm) than the 30-yr
 263 average (430 mm) with significant rainfall values in winter (303 mm) and spring (195
 264 mm) (Fig. 1d). In contrast, the two last cropping seasons analyzed were extremely dry
 265 (211 and 228 mm in the 2010-2011 and 2011-2012 seasons, respectively) (Fig. 1e and
 266 1f). The 2010-2011 season was characterized by a dry summer (42 mm), fall (1 mm)
 267 and winter (45 mm). Similarly, the 2011-2012 season was characterized by dry summer
 268 and winter periods, with only 35 mm and 15 mm, respectively. In 2010-2011 and 2011-
 269 2012, the spring rainfall was 123 and 132 mm, respectively, lower than the 30-yr
 270 average (144 mm).

271 **Sowing date and maturity class effects on barley yield and water- and N-use**
 272 **efficiency**

Barley yield and above-ground biomass were significantly affected by the interaction between maturity class and sowing date, and the sowing date x year and maturity class x year interactions (Table 1). As an average of the two maturity classes studied, D2 and D3 showed greater barley grain yields than D1 in the three cropping seasons studied (Fig. 2). The greatest grain yield of BEC was observed for D2, while for BMC both D2 and D3 presented greater yields than D1 (Table 1).

The number of spikes m^{-2} was significantly affected by sowing date, maturity class and year main effects but not interactions (Table 1). D1 and D2 showed a greater number of spikes m^{-2} than D3 as an average of maturity classes and cropping seasons. The number of grains per spike was significantly affected by the sowing date x year and maturity class x year interactions. An increased number of grains per spike was observed when the sowing date was delayed in 2006-2007 and 2008-2009, while in 2007-2008 the D2 treatment showed the greatest values (Fig. 2). Moreover, BMC had a greater number of grains per spike than BEC in the three cropping seasons. The TKW was significantly affected by all main effects and their interactions. Increased TKW was observed when the date of sowing was delayed in the three cropping seasons, with the exception of 2008-2009 for BEC (Fig. 2). The harvest index was affected by all the effects and their interactions, except the interaction between sowing date and maturity class (Table 1). Delaying sowing (D2 and D3 compared to D1) led to higher HI in 2006-2007 for both maturity classes (BMC and BEC) and in 2007-2008 for BMC (Fig. 2). However, that trend was not observed in 2008-2009.

Barley WU was only significantly affected by the interaction between year and sowing date ($P = 0.005$) (data not shown). Significant differences in WU between sowing dates were only observed in 2006-2007 with lower values for D1 compared to D2 and D3 (data not shown). Barley WUE_b and WUE_y were significantly affected by

sowing date x year and maturity class x year interactions. WUE_y was also affected by the interaction between sowing date and maturity class, and by the triple interaction (Table 1). Greater WUE_b was observed in D2 and D3 compared to D1 in 2006-2007 and 2008-2009 as an average of maturity classes, while D2 showed the highest values in 2007-2008 (Fig. 2). The WUE_y of BMC and BEC increased significantly when the sowing date was delayed from D1 to D2 and D3 (Fig. 2).

Barley NUE was significantly affected by the sowing date x maturity class, sowing date x year as well as maturity class x year interactions (Table 1). NUE increased significantly when the sowing date was delayed from D1 to D2 and D3 in 2006-2007 and 2008-2009, as an average of maturity class (Fig. 2). When distinguishing between maturity classes, the delay of sowing date (D2 and D3 compared to D1) also significantly increased barley NUE (Table 1).

Sowing date and maturity class effects on wheat yield and water- and N-use efficiency

Wheat grain yield was significantly affected by maturity class x sowing date, sowing date x year, as well as maturity class x year interactions (Table 2). Wheat above-ground biomass was significantly affected by the interaction between sowing date and year, and by the interaction between maturity class and year (Table 2). In 2009-2010 the delay of sowing led to an increase in grain yield and above-ground biomass, while the contrary result was observed in 2010-2011 and 2011-2012 (Fig. 3). The delay of sowing only positively affected the grain yield of WEC as an average of the three cropping seasons studied (Table 2).

The three wheat yield components studied were significantly affected by the interaction between sowing date and year (Table 2). In 2009-2010 the delay of sowing

led to greater number of spikes m^2 and grains per spike, but had no effect on TKW (Fig. 3). In contrast, in the 2010-2011 and 2011-2012 seasons lower TKW was observed when sowing was delayed, while in 2010-2011 the delay of sowing led to a lower number of grains per spike (Fig. 3). The wheat HI was significantly affected by the interaction between sowing date and maturity class, and the interaction between sowing date and year (Table 2). However, a delay in sowing produced no consistent trend in this variable.

Wheat WU was only affected by year ($P < 0.001$) with 2009-2010 > 2011-2012 > 2010-2011 (data not shown). Wheat WUE_b was affected by the interaction between maturity class and year, and the interaction between sowing date and year (Table 2). In turn, WUE_y was affected by year x sowing date interaction. The delay in sowing had contrary effects on WUE_b and WUE_y depending on the cropping season. Thus, while D2 and D3 showed higher WUE_b and WUE_y values than D1 in 2009-2010, the opposite trend was observed in 2010-2011 and 2011-2012 (Fig. 3). Wheat NUE was affected by maturity class and the interaction between sowing date and year (Table 2). Compared to D1, later sowing dates (i.e., D2 and D3) led to increased NUE in the 2009-2010 cropping season (Fig. 3). Moreover, greater NUE was observed in WMC than in WEC as an average of cropping seasons (Table 2).

The later barley sowings (D2 and D3) showed a significant linear relationship between grain yield and the number of spikes m^2 , no significantly different between them at $P < 0.05$. Contrarily, no relationship was found in D1 (Fig. 4a) ($P = 0.76$). As a difference, the three barley sowing dates (D1, D2 and D3) showed the same ($P < 0.05$) linear relationship between the number of grains per spike and grain yield (Fig. 4b). No relationship was found between TKW and barley grain yield ($P = 0.17$). In the case of wheat, grain yield was linearly related to the number of spikes m^2 and to the number of

347 grains per spike, with no differences between sowing dates according to the analysis of
348 covariance performed (Fig. 4d, 4e). In contrast, wheat TKW showed a non-significantly
349 different linear relationship with grain yield between D2 and D3, while no relationship
350 was found for D1 at $P < 0.05$ (Fig. 4f).

351

352 DISCUSSION

353 Sowing date delay and maturity class effects on barley and wheat yields and yield 354 components

355 The delay of sowing date had a positive influence on grain yield in the three
356 seasons cropped with barley, and in the first season cropped with wheat (a wet year).
357 The improved performance of barley in 2/3 years and wheat in 1/3 years from delayed
358 sowing dates in the rainfed semi-arid conditions of the experiment could be explained
359 by a better synchronization between water use and crop requirements. Rainfall
360 distribution during the growing season and water storage during summer fallow play a
361 major role on winter cereal production in dryland Mediterranean areas (Basso et al.,
362 2012; Sadras et al., 2012; Lampurlanés et al., 2016). The lower number of grains per
363 spike and TKW in D1 indicates increased water deficit when these yield components
364 were determined compared to the later sowings. García del Moral et al. (2003) pointed
365 out that under poor conditions a reduced tillering rate can become a useful trait for
366 conserving resources that are more efficiently used during the critical phases of yield
367 determination. Terminal drought represents one of the key factors in yield reduction in
368 water-limited areas (González et al., 2007).

369 The increased number of grains per spike and TKW in the three seasons of
370 barley and the first season of wheat, observed for D2 and D3, could also have been
371 favored by the rainfall received during the late spring, in similar or greater quantities
372 than the historical average, which is better used by crops. Late spring rains often occur
373 in western Mediterranean regions. The increased number of grains per spike and greater
374 TKW would explain the greater barley harvest index in the 2006-2007 and 2007-2008
375 seasons for the D2 and D3 sowing dates. In contrast, in the 2008-2009 season there was

376 more rainfall during the fall, which significantly enhanced the production of above-
377 ground barley biomass in D2 and D3 and slightly reduced the HI.

378 In Mediterranean areas with colder fall conditions than those in our experiment
379 greater yields have been reported at earlier sowing dates due to a longer season
380 (Richards et al., 2014; Stephens and Lyons, 1998). However, according to our results, in
381 regions with a mild fall this general assumption does not apply. In this regard, as our
382 data suggest, the use of longer maturity classes of barley (i.e. BMC vs. BEC) at an early
383 sowing date could lead to a water deficit during the grain filling period, resulting in
384 lower TKW and reducing crop yields. Interestingly, the opposite was found to be true
385 for wheat, where a lower yield was observed in WEC compared to WMC as an average
386 of cropping seasons. This result could be explained by the erratic nature of spring
387 rainfall which defines a narrow and highly variable window of late water available to
388 crops, favoring different maturity classes depending on the cropping season.

389 Under the western Mediterranean conditions of the experiment the first half of
390 fall presents warm temperatures that do not limit the development of certain pathogens
391 and weeds. At the experimental site, the 30-yr air temperature averages for October and
392 November are 14.5 and 7.9 °C, respectively. The use of NT combined with the early
393 sowing of cereal monocrops favor the development of small-seeded grasses such as
394 ripgut brome. During the experimental period no active ingredients were commercially
395 available for the post-emergence control of this weed under barley production, relying
396 solely on non-selective pre-sowing herbicides (glyphosate). However, this herbicide is
397 more effective for delayed sowing dates since (i) the window of weed emergence during
398 fall rains is longer, and (ii) wetter soil conditions favor glyphosate uptake by weeds. In
399 our experiment, García et al. (2014) measured ripgut brome density in the 2008-2009,
400 2009-2010 and 2010-2011 seasons at herbicide applications. For the D1, D2 and D3

sowing dates ripgut brome density was recorded as 540, 105 and 32 plants m^{-2} in 2008-2009; 1284, 27 and 9 plants m^{-2} in 2009-2010; and 102, 3 and 1 plants m^{-2} in 2010-2011 (García et al., 2014). Thus, the greater yields reached in D2 and D3 compared to D1 in the three seasons of barley and in the first year of wheat could be also partly explained by less competition with weeds for water. In the case of wheat, the competition between the crop and weeds would have been lower in subsequent seasons (2010-11 and 2011-12) given the application of a selective herbicide to control ripgut brome which reduced significantly the seedbank of this weed as García et al. (2014) showed.

Sowing date delay and maturity class effects on water- and nitrogen-use efficiency

In the case of barley, WU only differed between sowing dates for the 2006-2007 harvest, with lower values for D1. Lower biomass was caused by reduced water uptake. Therefore, increased WUE in D2 and D3 was the result of increased biomass. However, in the case of wheat, which has a longer development period than barley, cultivars sown at delayed dates may reduce WUE_y and NUE as a result of a water deficit during the grain filling period. This latter aspect appears to be corroborated by the decreased wheat WUE_y observed in D3 in the 2010-2011 season, as well as in D2 and D3 in the 2011-2012 season, when there was an important water deficit for much of the growing cycle. Compared to 2009-10, there was a 57% and 53% reduction in WU in 2010-2011 and 2011-2012, which led to a strong diminution in the yield components. In severely water-limited western Mediterranean areas, farmers tend to favor barley over wheat, given the shorter cycle of the former, aiming at reducing terminal drought effects as much as possible (Ryan et al., 2008). Our data corroborates that late wheat sowings perform poorly in very dry years.

Soil mineral N at sowing and N use did not differ significantly between treatments during the barley cropping seasons. However, a lower mineral N content at sowing would be expected for the most productive sowing dates, resulting from increased N uptake. The observed result could be the consequence of greater N uptake by grass weeds in D1. The role played by other processes in the N cycle, mainly losses, would be secondary. In average years, well-managed Mediterranean dryland agroecosystems lose little N through leaching and denitrification. Regarding to this, in a contiguous experiment managed under NT and similar rates of N, Plaza-Bonilla et al. (2014) reported a loss of N of less than $0.5 \text{ kg N}_2\text{O-N yr}^{-1}$. According to Angás et al. (2006) the area presents highly unusual rainfall conditions for leaching, which occurs once every 7-10 years. However, N losses by volatilization can be very high in specific cases (Sanz-Cobena et al., 2008). Despite ammonia volatilization could have been a major loss pathway given the pH of the soil of the experiment and the type of fertilizer used, the use of urea-ammonium nitrate solutions in the area has become a common farmers' practice in the area given it is cheaper, easy to use and it gives the possibility to mix the tank with pesticides. Therefore, as Angás et al. (2006) suggested, the development of injection techniques would be a valuable way to improve the efficiency of fertilizer.

The two-fold increase in barley NUE values in 2008-2009, characterized by a wet spring, demonstrates the principal role played by water availability at the end of the season in the more efficient use of nitrogen. However, this result could also be partially explained by the lower amount of mineral N available at sowing, which was 266, 179 and 94 kg N ha^{-1} for the 2006-2007, 2007-2008 and 2008-2009 seasons, as an average of the treatments. The decreased soil N availability resulted from the lower quantities of mineral N rate applied during the experiment (i.e. 50 kg N ha^{-1}) compared with the rate

449 applied by the farmer (double or more in some cases). In our experiment that rate was
 450 established in order to achieve a soil status that was less susceptible to N losses to the
 451 environment.

452 Wheat maturity class choice played a major role in WUE_y and NUE. The shorter
 453 cycle of WEC than WMC could have reduced the susceptibility to terminal drought,
 454 increasing WUE_y and NUE.

455 **CONCLUSIONS**

456 No-till farming is an increasingly adopted soil management practice in semi-arid
 457 dryland areas. Among other benefits, it facilitates the delay of cereal sowing date due to
 458 improved trafficability, widening the window for sowing and partly avoiding mild
 459 temperatures in the western Mediterranean that increase susceptibility to pests, weeds
 460 and diseases. In our work, the delay of sowing (from October to mid-November and
 461 beginning of December) increased yield in years with normal (or greater than normal)
 462 rainfall, 2/3 years in barley and 1/3 years in wheat. The increased water availability in
 463 later stages when delaying sowing led to better conditions for defining the number of
 464 grains per spike and the TKW. Delayed sowing in average years maximized resource
 465 use efficiency for water and nitrogen, increasing the sustainability of the system.
 466 However, in years with extreme drought conditions (such as 2010-2011 and 2011-2012
 467 in our experiment), the delay in sowing increased susceptibility to terminal drought,
 468 negatively affecting the TKW and reducing grain yield. Although we only compared
 469 two cultivars of each species, the data suggests that the best combination of sowing date
 470 and maturity class is highly dependent on the erratic rainfall during late spring.

471 **Acknowledgements**

472 This work was supported by the Comisión Interministerial de Ciencia y
473 Tecnología of Spain (Project Grants AGL2007-66320-C02-01/AGR and AGL2010-
474 22050-C03-01). DPB received a “*Juan de la Cierva-Formación*” postdoctoral grant
475 from the Ministerio de Economía y Competitividad of Spain (ref. FJCI-2014-19570).
476 We thank Silvia Martí, Carlos Cortés and Miquel Betriu for their technical assistance.

477 REFERENCES

- 478 Álvaro-Fuentes, J., J. Lampurlanés, and C. Cantero-Martínez. 2009. Alternative crop
479 rotations under Mediterranean no-tillage conditions: biomass, grain yield, and
480 water-use efficiency. *Agron. J.* 101:1227-1233.
- 481 Angás, P., J. Lampurlanés, and C. Cantero-Martínez. 2006. Tillage and N fertilization
482 effects on N dynamics and barley yield under semiarid Mediterranean conditions.
483 *Soil & Till. Res.* 87:59-71.
- 484 Basso, B., C. Fiorentino, D. Cammarano, G. Cafiero, and J. Dardanelli. 2012. Analysis
485 of rainfall distribution on spatial and temporal patterns of wheat yield in
486 Mediterranean environment. *Eur. J. Agron.* 41:52-65.
- 487 Bueno, J., C. Amiama, J.L. Hernanz, and J.M. Pereira. 2006. Penetration resistance, soil
488 water content, and workability of grassland soils under two tillage systems. *T.*
489 *ASABE* 49:875-882.
- 490 Cantero-Martínez, C., P. Angás, and J. Lampurlanés. 2003. Growth, yield and water
491 productivity of barley (*Hordeum vulgare* L.) affected by tillage and N fertilization in
492 Mediterranean semiarid, rainfed conditions of Spain. *Field Crop Res.* 84:341-357.
- 493 Cantero-Martínez, C., P. Angás, and J. Lampurlanés. 2007. Long-term yield and water
494 use efficiency under various tillage systems in Mediterranean rainfed conditions.
495 *Ann. Appl. Biol.* 150:293-305.
- 496 Cantero-Martínez, C., D. Plaza-Bonilla, P. Angás, and J. Álvaro-Fuentes. 2016. Best
497 management practices of tillage and nitrogen fertilization in Mediterranean rainfed
498 conditions: Combining field and modelling approaches. *Eur. J. Agron.* 79:119-130.

- 499 Cantero-Martínez, C., J.M. Villar, I. Romagosa, and E. Fereres. 1995. Nitrogen
500 fertilization of barley under semi-arid rainfed conditions. *Eur. J. Agron.* 4:309-316.
- 501 Connor, D.J., and R.S. Loomis. 1991. Strategies and tactics for water-limited agriculture
502 in low rainfall Mediterranean climates. In: Acevedo, E., C. Giménez, E. Fereres, and
503 J.P. Srivastava. (Eds). *Improvement and management of winter cereals under*
504 *temperature, drought and salinity stresses. Proceedings of the ICARDA-INIA*
505 *Symposium, Madrid, Spain, pp. 441–465.*
- 506 Cooper, P.J.M., P.J. Gregory, D. Tully, and H.C. Harris. 1987. Improving water-use
507 efficiency of annual crops in the rain-fed farming systems of West Asia and North-
508 Africa. *Exp. Agr.* 23:113-158.
- 509 García, A.L., J. Torra, A. Royo-Esnal, C. Cantero-Martinez, and J. Recasens. 2014.
510 Integrated management of *Bromus diandrus* in dryland cereal fields under no-till.
511 *Weed Res.* 54:408-417.
- 512 García del Moral, L.F., M.B. García del Moral, J.L. Molina-Cano, and G.A. Slafer.
513 2003. Yield stability and development in two- and six-rowed winter barleys under
514 Mediterranean conditions. *Field Crop Res.* 81:109-119.
- 515 González, A., I. Martín, and L. Ayerbe. 2007. Response of barley genotypes to terminal
516 soil moisture stress: phenology, growth and yield. *Aust. J. Agr. Res.* 58:29-37.
- 517 Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In:
518 Dane, J.H., and G.C. Topp. (Eds) *Methods of soil analysis. Part 4. Physical*
519 *methods. SSSA Book Ser. 5. SSSA, Madison, pp 201–228*
- 520 Kirkegaard, J.A., J.R. Hunt, T.M. McBeath, J.M. Lilley, A. Moore, K. Verburg, M.
521 Robertson, Y. Oliver, P.R. Ward, S. Milroy, and A.M. Whitebread. 2014. Improving

- 522 water productivity in the Australian grains industry – a nationally coordinated
523 approach. *Crop Pasture Sci.* 65:583–601
- 524 Lampurlanés, J., D. Plaza-Bonilla, J. Álvaro-Fuentes, and C. Cantero-Martínez. 2016.
525 Long-term analysis of soil water conservation and crop yield under different tillage
526 systems in Mediterranean rainfed conditions. *Field Crop Res.* 189:59-67. DOI:
527 10.1016/j.fcr.2016.02.010.
- 528 Loss, S.P., and K.H.M. Siddique. 1994. Morphological and physiological traits
529 associated with wheat yield increases in Mediterranean environments. *Adv. Agron.*
530 52:229-276.
- 531 Mahdi, L., C.J. Bell, and J. Ryan. 1998. Establishment and yield of wheat (*Triticum*
532 *turgidum* L.) after early sowing at various depths in a semi-arid Mediterranean
533 environment. *Field Crop Res.* 58:187-196.
- 534 McAneney, K.J., and J.L. Arrúe, J.L. 1993. A wheat-fallow rotation in northeastern
535 Spain: water balance-yield considerations. *Agronomie* 13:481-490.
- 536 Piggin, C., A. Haddad, Y. Khalil, S. Loss, and M. Pala. 2015. Effects of tillage and time
537 of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed
538 systems in Syria. *Field Crop Res.* 173:57-97.
- 539 Plaza-Bonilla, D., J. Álvaro-Fuentes, J.L. Arrúe, and C. Cantero-Martínez. 2014. Tillage
540 and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed
541 Mediterranean area. *Agric. Ecosys. Environ.* 189:43-52.
- 542 Plaza-Bonilla, D., C. Cantero-Martínez, J. Bareche, J.L. Arrúe, J. Lampurlanés, and J.
543 Álvaro-Fuentes. 2017. Do no-till and pig slurry application improve barley yield and

- 544 water and nitrogen use efficiencies in rainfed Mediterranean conditions? *Field Crop*
545 *Res.* 203:74-85.
- 546 Ramos, J.M., M.B. García del Moral, J. Marinetto, and L.F. García del Moral. 1993.
547 Sowing date and cutting frequency effects on triticale forage and grain production.
548 *Crop Sci.* 33:1312-1315.
- 549 Richards, R.A., J.R. Hunt, J.A. Kirkegaard, and J.B. Passioura. 2014. Yield
550 improvements and adaptation of wheat to water-limited environments in Australia-a
551 case study. *Crop Pasture Sci.* 65:676-689.
- 552 Ryan, J., M. Singh, and M. Pala. 2008. Long-term cereal-based rotation trials in the
553 Mediterranean region: implications for cropping sustainability. *Adv. Agron.* 97:273-
554 319.
- 555 Sadras, V.O., C. Lawson, P. Hooper, and G.K. Mc Donald. 2012. Contribution of
556 summer rainfall and nitrogen to the yield and water use efficiency of wheat in
557 Mediterranean-type environments of South Australia. *Eur. J. Agron.* 36:41-54.
- 558 Santiveri, F., J. Lloveras, S. Martí and C. Cantero-Martínez. 2004. Crop emergence and
559 early crop growth of barley affected by crop residue under different tillage systems
560 and N fertilization rates in semiarid conditions of Northeast Spain. In: Cantero, C.
561 and D. Gabiña (eds.). *Mediterranean rainfed agriculture: strategies for sustainability.*
562 *Options Méditerranées.* Vol. 60: 63-72. ISBN: 2-85352-294-6.
- 563 Sanz-Cobena, A., T.H. Misselbrook, A. Arce, J.I. Mingot, J.A. Diez, and A. Vallejo.
564 2008. An inhibitor of urease activity effectively reduces ammonia emissions from
565 soil treated with urea under Mediterranean conditions. *Agric. Ecosys. Environ.*
566 126:243-249.

- 567 SAS Institute Inc., 2014. Using JMP1 11, Second edition SAS Institute Inc., Cary, NC.
- 568 Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, and J. Roger-Estrade. 2012.
- 569 No-till in northern, western and south-western Europe: A review of problems and
- 570 opportunities for crop production and the environment. *Soil Till. Res.* 118:66-87.
- 571 Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources
- 572 Conservation Service, Washington, DC.
- 573 Stephens, D.J., and T.J. Lyons. 1998. Variability and trends in sowing dates across the
- 574 Australian wheatbelt. *Aust. J. Agric. Res.* 49:1111-1118.
- 575 Thackray, D.J., A.J. Diggle, and R.A.C. Jones. 2009. BYDV PREDICTOR: a
- 576 simulation model to predict aphid arrival, epidemics of *Barley yellow dwarf virus*
- 577 and yield losses in wheat crops in Mediterranean-type environment. *Plant Pathol.*
- 578 58:186-202.
- 579 Unger, P.W., Stewart, B.A., Parr, J.F., and R.P. Singh. 1991. Crop residue management
- 580 and tillage methods for conserving soil and water in semi-arid regions. *Soil Till.*
- 581 *Res.* 20:219-240.
- 582 Wolf, D.D., and K.L. Edmisten. 1989. Late season alfalfa plantings: conventional vs.
- 583 no-till methods. *Crop Sci.* 29:170-175.

584 **Figure captions**

585 **Fig. 1** Weekly precipitation (columns), and average maximum (black circles) and
 586 minimum (white circles) temperatures at the Agramunt experimental site: 30-yr average
 587 and cropping seasons studied (from 2006-2007 to 2008-2009 for barley and from 2009-
 588 2010 to 2011-2012 for wheat). At the top of each sub-figure the grey-edged symbols
 589 indicate the dates of sowing, anthesis and physiological maturity for the D1 (circles),
 590 D2 (triangles) and D3 (squares) sowing dates and for the early- (black-filled symbols)
 591 and medium (empty symbols) maturity classes. Note the different Y-axes.

592 **Fig. 2** Barley grain yield, above-ground biomass, spikes m^{-2} , grains spike $^{-1}$, thousand
 593 kernel weight (TKW), harvest index, water-use efficiency for biomass and yield (WUE_b
 594 and WUE_y) and nitrogen-use efficiency (NUE) during the 2006-2007, 2007-2008 and
 595 2008-2009 cropping seasons as affected by sowing date (D1-October, D2-November,
 596 and D3-December) and maturity class (medium, BMC; early, BEC). Vertical bars
 597 indicate standard deviation. For a given year, different lower-case letters indicate
 598 significant differences between sowing dates and maturity classes. For a given year,
 599 different lower-case italic letters and different upper-case letters indicate significant
 600 differences between sowing dates and maturity classes, respectively ($P < 0.05$, LSD test).

601 **Fig. 3** Wheat grain yield, above-ground biomass, spikes m^{-2} , grains spike $^{-1}$, thousand
 602 kernel weight (TKW), harvest index, water-use efficiency for biomass and yield (WUE_b
 603 and WUE_y) and nitrogen-use efficiency (NUE) during the 2009-10, 2010-11 and 2011-
 604 12 cropping seasons as affected by sowing date (D1-October, D2-November, and D3-
 605 December) and maturity class (medium, WMC; early, WEC). Vertical bars indicate
 606 standard deviation. For a given year, different lower-case letters indicate significant
 607 differences between sowing dates and maturity classes. For a given year, different
 608 lower-case italic letters and different upper-case letters indicate significant differences
 609 between sowing dates and maturity classes, respectively ($P < 0.05$, LSD test).

610 **Fig. 4** Linear relationship between grain yield and spikes m^{-2} , grains spike $^{-1}$ and
 611 thousand kernel weight (TKW) of barley (a, b and c, respectively) and wheat (d, e and f,
 612 respectively) as affected by sowing date (D1-October, D2-November, and D3-
 613 December). Each legend shows the sowing dates with the same significant linear

614 relationship at $P < 0.05$. Non-significant linear relationships are not shown. Note the
615 different axes.

616 **Table 1** Analysis of variance of barley grain yield, above-ground biomass, spikes m⁻², grains spike⁻¹, thousand kernel weight (TKW), harvest
617 index (HI), water-use efficiency for above-ground biomass (WUE_b) and grain yield (WUE_y), and nitrogen use efficiency (NUE) as affected by
618 sowing date (D1, October; D2, November, and D3, December), maturity class (BEC and BMC, barley early and medium maturity class,
619 respectively) and year, and their interactions.

Treatments and ANOVA effects	Grain yield	Abg. biomass	Spikes m ⁻²	Grains spike ⁻¹	TKW	HI	WUE _b	WUE _y	NUE
	-- kg ha ⁻¹ --	-- g m ⁻² --			-- g--		-- kg ha ⁻¹ mm ⁻¹ --	-- kg ha ⁻¹ mm ⁻¹ --	-- kg ha ⁻¹ kg N ⁻¹ --
D1 (October)	2481 c†	792 b	843 a	12 b	35.0 c	0.46 b	20.4 b	6.4	10.8 b
D2 (November)	3946 a	1029 a	895 a	15 a	38.5 b	0.50 a	26.2 a	10.0	17.1 a
D3 (December)	3623 b	949 a	729 b	16 a	40.5 a	0.51 a	23.7 a	8.9	14.4 a
BEC	3336	897	888 a	13 b	41.1 a	0.50 a	22.8	8.4	14.4 a
BMC	3364	957	757 b	17 a	35.0 b	0.47 b	24.1	8.7	13.8 b
2006-07	3418 b	1011 a	1034 a	14 b	31.0 b	0.43 c	29.5 a	9.9	9.9 b
2007-08	2519 a	660 b	625 c	14 b	41.3 a	0.53 a	18.6 b	7.3	9.8 b
2008-09	4113 c	1092 a	808 b	16 a	41.8 a	0.50 b	22.3 b	8.4	24.2 a
D1-BEC	2635 c	779 d	942	10	38.7 c	0.47	20.4	6.7 d	12.6 b
D2-BEC	3892 a	929 bc	940	13	40.5 b	0.51	23.7	9.7 ab	17.4 a
D3-BEC	3481 b	982 b	783	14	44.1 a	0.53	24.3	8.7 c	12.8 a
D1-BMC	2326 d	806 cd	745	15	31.4 e	0.45	20.5	6.1 d	9.0 c
D2-BMC	4001 a	1130 a	851	17	36.5 d	0.48	28.8	10.3 a	16.8 a
D3-BMC	3765 a	917 bcd	675	18	36.9 d	0.49	23.1	9.1 bc	15.9 a
<i>ANOVA</i>									
<i>P-values</i>									
Sowing date (SD)	<0.001	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Maturity class (C)	0.728	0.133	0.003	<0.001	<0.001	<0.001	0.370	0.313	0.012
Year (Y)	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001
SD x C	0.013	0.037	0.513	0.505	<0.001	0.447	0.055	0.014	0.007
SD x Y	<0.001	<0.001	0.095	<0.001	<0.001	<0.001	0.009	<0.001	<0.001
C x Y	<0.001	0.003	0.133	0.003	<0.001	<0.001	0.049	<0.001	<0.001
SD x C x Y	0.078	0.014	0.373	0.881	0.010	<0.001	0.182	0.002	0.120

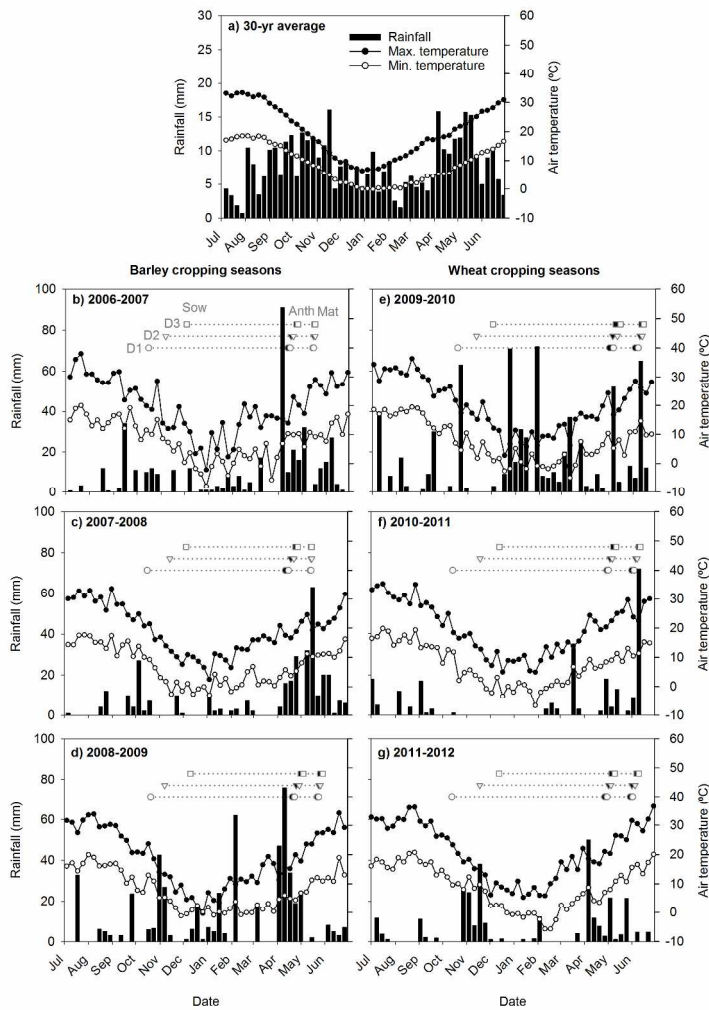
620 † For a given variable, different letters indicate significant differences between treatments at *P* < 0.05 (LSD test).

621

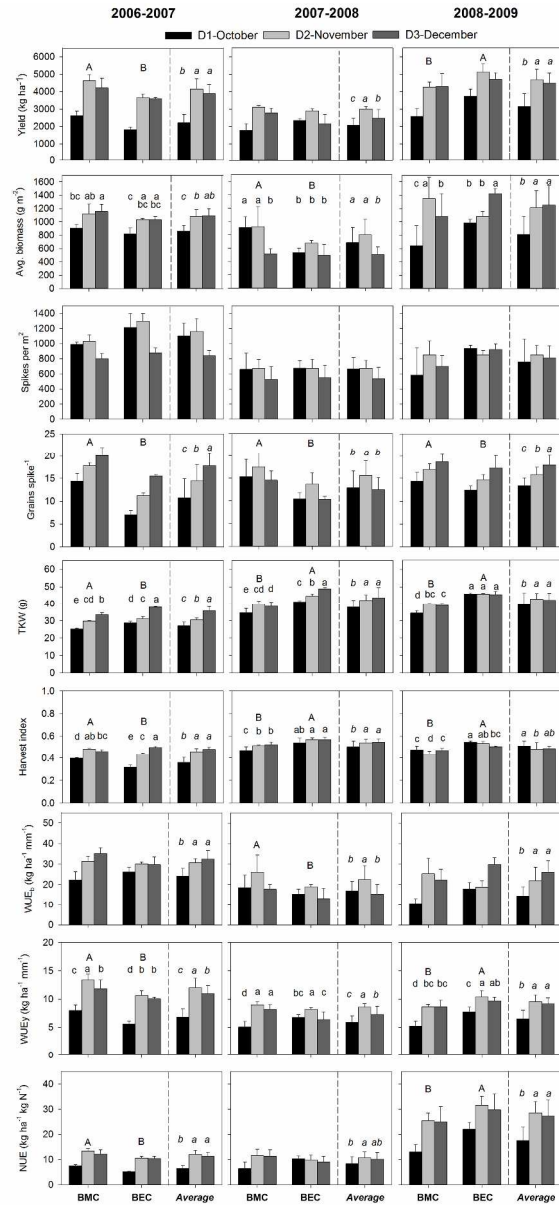
622 **Table 2** Analysis of variance of wheat grain yield, above-ground biomass, spikes m⁻², grains spike⁻¹, thousand kernel weight (TKW), harvest
 623 index (HI), water-use efficiency for above-ground biomass (WUE_b) and grain yield (WUE_y), and nitrogen use efficiency (NUE) as affected by
 624 sowing date (D1, October; D2, November, and D3, December), maturity class (WEC and WMC, wheat early and medium maturity class,
 625 respectively) and year, and their interactions.

Treatments and ANOVA effects	Grain yield	Abg. biomass	Spikes m ⁻²	Grains spike ⁻¹	TKW	HI	WUE _b	WUE _y	NUE
	-- kg ha ⁻¹ --	-- g m ⁻² --			-- g--		-- kg ha ⁻¹ mm ⁻¹ --	-- kg ha ⁻¹ mm ⁻¹ --	-- kg ha ⁻¹ kg N ⁻¹ --
D1 (October)	1183 b†	570 b	322	26 b	30 a	0.43	19	4.0	7.2 b
D2 (November)	1572 a	732 a	349	33 a	27 b	0.45	20	4.4	10.1 a
D3 (December)	1625 a	656 ab	335	30 a	25 c	0.43	17	4.0	10.2 a
WMC	1541 a	659	346	30	26 b	0.44	17 b	4.3	9.9 a
WEC	1379 b	647	324	30	29 a	0.44	20 a	4.0	8.4 b
2009-10	2198 a	907 a	373 a	35 a	32 a	0.47 a	16 b	3.9 b	13.6 a
2010-11	1185 b	521 b	275 b	31 b	26 b	0.46 a	22 a	4.8 a	6.0 c
2011-12	997 c	532 b	358 a	24 c	24 c	0.39 b	18 b	3.7 b	7.8 b
D1-WMC	1393 a	617	337	30 b	29	0.45 a	19	4.5	8.7
D2- WMC	1576 a	737	366	31 ab	26	0.45 ab	18	4.3	10.4
D3- WMC	1654 a	622	335	29 b	24	0.42 bc	16	4.1	10.7
D1-WEC	973 b	524	307	23 c	31	0.42 c	19	3.5	5.8
D2- WEC	1568 a	728	332	35 a	29	0.45 ab	22	4.5	9.7
D3- WEC	1596 a	691	334	32 ab	26	0.44 abc	19	4.0	9.6
ANOVA					P-values				
Sowing date (SD)	0.004	0.013	0.277	0.001	<0.001	0.228	0.254	0.323	0.003
Maturity class (C)	0.008	0.791	0.122	0.913	<0.001	0.377	0.028	0.153	0.040
Year (Y)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
SD x C	0.009	0.307	0.566	0.010	0.689	0.012	0.753	0.089	0.426
SD x Y	<0.001	<0.001	<0.001	<0.001	0.001	0.006	<0.001	<0.001	<0.001
C x Y	0.025	0.022	0.002	0.536	0.042	0.615	0.035	0.136	0.505
SD x C x Y	0.055	0.922	0.366	0.179	0.001	0.128	0.884	0.223	0.631

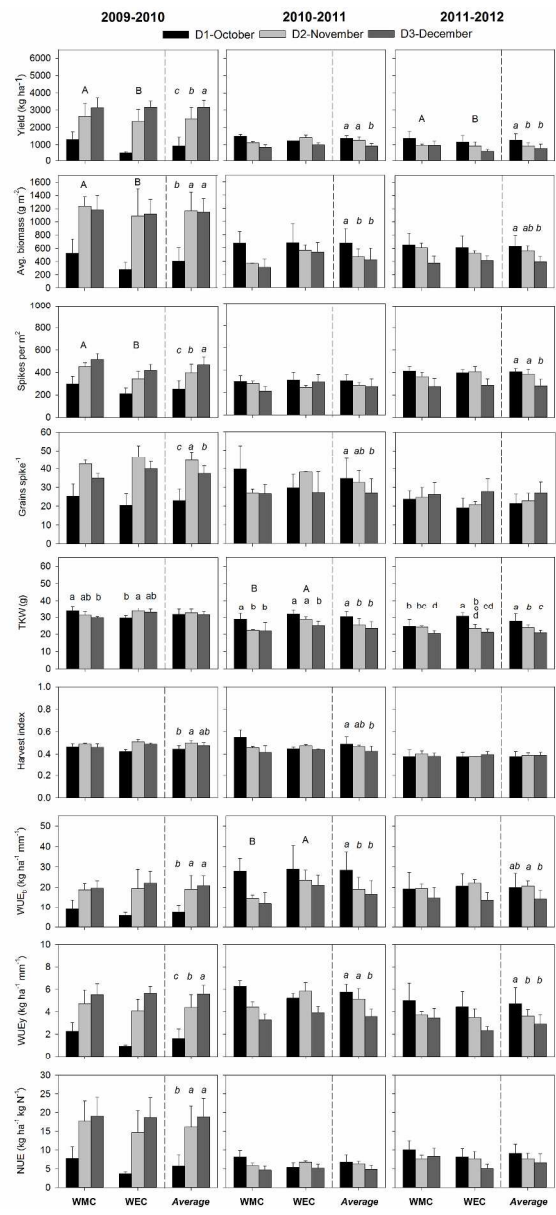
† For a given variable, different letters indicate significant differences between treatments at $P < 0.05$ (LSD test).



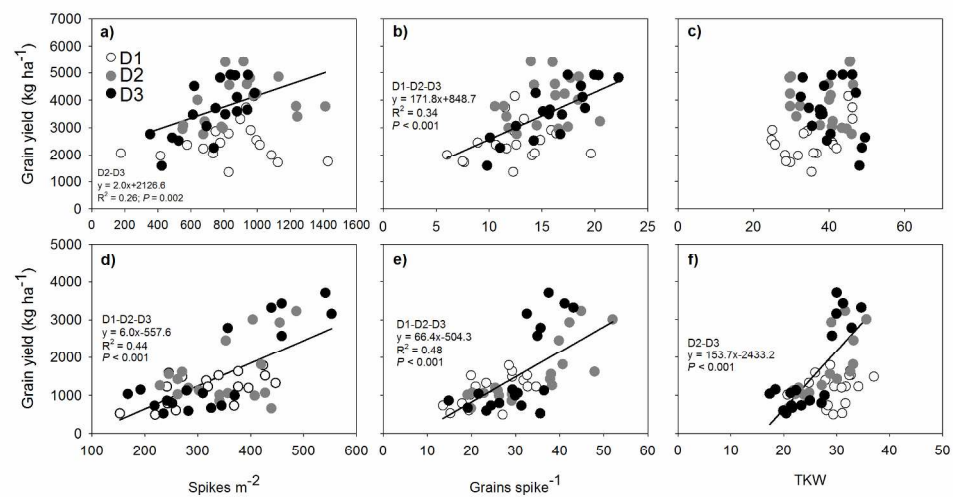
274x287mm (300 x 300 DPI)



242x438mm (300 x 300 DPI)



247x442mm (300 x 300 DPI)



223x131mm (300 x 300 DPI)